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TO: Y. Cho HEP

FROM: W. Praeg ETP

SUBJECT: Frequency Response of Storage Ring Magnets, Eddy Current Shielding of Vacuum Chamber

It is planned to use feedback to correction coils on ring magnets to reduce beam motion at frequencies of 120 Hz or less.

The magnet cores, made from 1.5 mm thick laminations of 1010 steel, will readily carry flux of $\leq$ 400 Hz. However, due to eddy currents, the aluminum vacuum chamber will attenuate verticle ac fields above 8 Hz and horizontal fields above 25 Hz. Eddy currents will also cause phase shifts between the field generated by the correction coils, B_o, and the field inside the vacuum chamber B_i. These problems do not exist with a stainless steel vacuum chamber.

Discussed below are the frequency response of the ring magnets, and the eddy current shielding of our present aluminum vacuum chamber and of a stainless steel chamber with a wall 1/8" thick.

1. Frequency Response of Ring Magnets

The required ac corrections are assumed to be ± 1% of the ± 1 kG dc corrections which provide ± 400 G-m in the 0.4 m long sextupoles. At small alternating fields (B < 10 G), hysteresis losses are negligible and the incremental permeability μ_Δ decreases to its lower limit, the reversible permeability μ_r. Both μ_Δ and μ_r are dependent on the value of dc magnetization present and on the magnetic history of the material. The maximum value of μ_r is reached when the material is completely demagnetized where it becomes equivalent to the initial permeability μ_i. For 1010 steel, we have $\mu_i = \hat{\mu}_r \cong 200$ which, at fields $\cong$ 10 kG, reduces to $\mu_r < 100$.

As a measure of the penetration of the surface field H_o into the interior of a plate being parallel to the field, it is customary to use the skin depth defined as

$$\delta = \left(\frac{\rho}{\mu\pi f}\right)^{1/2} \tag{1}$$

where

ρ = resistivity = 15×10^{-6} Ω cm for 1010 steel,
$\mu = \mu_o\mu_r = 0.4\ \pi \times 10^{-8}\ \Omega s\ cm^{-1}\ \mu_r = 1.26 \times 10^{-6}\ \Omega s\ cm^{-1}$,
f = frequency s^{-1}.

It is common to distinguish between the frequency range of approximately uniform field distribution, where the lamination thickness $d < 2\delta$, and frequencies where skin effects are pronounced, $d > 2\delta$. The boundary between these two frequency ranges has been defined so that

$$d = 2\delta. \tag{2}$$

This cutoff frequency defined by (1) and (2) is

$$f_c = \frac{4\rho}{\mu\pi d^2} \tag{3}$$

For our magnet laminations, we have

$$f_c = \frac{4 \times 15 \times 10^{-6}\Omega cm}{1.26 \times 10^{-6}\Omega s cm^{-1}\pi 0.15^2 cm^2} = 673\ \text{Hz}$$

corresponding to a skin depth of 0.075 cm; there are no eddy current problems with our core laminations at 120 Hz. Assuming circular copper conductors for the correction coils, we have no eddy current problems as long as the conductor radius r_{Cu} is smaller than the skin depth of copper at 120 Hz. With

$$r < \delta = \left(\frac{1.73 \times 10^{-6}\Omega cm}{1.26 \times 10^{-8}\Omega s cm^{-1}\pi 120 s^{-1}}\right)^{1/2} = 0.6\ \text{cm}$$

this is no problem. We could, therefore, use the dc correction coils (± 1 kG) to make the ac corrections (± 10 G).

2. Eddy Current Shielding by the Aluminum Vacuum Chamber

2.1 Horizontal Fields (vertical corrections)

For horizontal fields, we can approximate the vacuum chamber, shown in Fig. 1, with a cylinder of inside radius r_i = 2.09 cm and outside radius r_o = 3.36 cm, having a wall thickness of d = 1.27 cm. Due to eddy currents in the vacuum chamber, the external field H_o is attenuated and phase shifted resulting in a field H_i inside the vacuum chamber. The attenuations a_s of a cylinder is defined by

$$a_s = \ln \left| \frac{H_o}{H_i} \right| \tag{4}$$

From reference [1], we obtain

$$a_s = \frac{1}{2} \ln \Big[\left(\frac{r_i}{2\delta}\right)^2 \left(\cosh \frac{2d}{\delta} - \cos \frac{2d}{\delta}\right)$$

$$+ \frac{r_i}{2\delta} \left(\sinh \frac{2d}{\delta} - \sin \frac{2d}{\delta}\right)$$

$$+ \frac{1}{2}\left(\cosh \frac{2d}{\delta} + \cos \frac{2d}{\delta}\right)\Big]. \tag{5}$$

Figure 2 shows the attenuation, calculated from Eq. (5), as a function of d/δ, which is proportional to the square root of the frequency, for different parameters $p = r_i/2d$. For low frequencies ($d < \delta$) and for high frequencies ($d > \delta$), Eq. (5) can be simplified to

$$a_s = \frac{1}{2} \ln[1 + (\frac{r_i d}{\delta^2})^2] \qquad \text{for } d < \delta, \qquad (6)$$

$$a_s = \frac{d}{\delta} + \ln \frac{r_i}{2\sqrt{2}\delta} \qquad \text{for } d > \delta. \qquad (7)$$

For horizontal fields, we have $p = 2.09/(2 \times 1.27) = 0.82$. For aluminum $\rho = 2.78 \times 10^{-6}$ Ωcm, and the skin depth is with $\delta = 8.38/\sqrt{f}$ and $d/\delta = 1.27/(8.38/\sqrt{f}) = 0.152\sqrt{f}$. The ratio of the outside field (H_o) to the field at the beam orbit (H_i) is shown below for various frequencies

f	1	5	8	14	25	125	625	Hz
$\frac{H_o}{H_i}$	1	1	1	1.1	1.3	7.0	100	

The aluminum vacuum chamber is an effective shield for frequencies above 25 Hz.

2.2 Vertical Fields (horizontal corrections)

The losses are estimated by approximating the vacuum chamber with a cylinder of $r_i = 7.73$ cm and $r_o = 9$ cm, $d = 1.27$ cm. This results in $p = 7.73/(2 \times 1.27) = 3.04$. The attenuation for various frequencies is shown below

f	1	5	8	14	25	125	625	Hz
$\frac{H_o}{H_i}$	1	1.2	1.5	2.8	4.8	28	630	

From inspection of Fig. 1, one sees that approximating the configuration of the vacuum chamber for vertical fields with a cylinder of $r_i = 7.73$ cm is not as good as it is for horizontal fields ($r_i = 2.09$ cm). Therefore, R. Lari calculated the shielding affect of the chamber using the program PE2D. His results are tabulated below

f	1	5	8	14	25	125	625	Hz
$\frac{H_o}{H_i}$	1	1.29	1.86	5.55	17.4	34.9	1534	

Figures 3, 4, and 5 show the flux distribution for 8 Hz, 14 Hz, and 25 Hz, respectively.

The attenuation especially above 14 Hz is larger than as given by the cylinder approximation. However, both methods show that frequencies above 8 Hz are severely attenuated.

Conclusion: The aluminum vacuum chamber will allow horizontal fields (vertical corrections) of $\leq$ 25 Hz; vertical fields (horizontal corrections) are restricted to $\leq$ 8 Hz.

3. Eddy Current Shielding of a Stainless Steel Vacuum Chamber

A stainless steel chamber could have a wall thickness d $\leq$ 1/8" = 0.32 cm. With a resistivity of 75×10^{-6} Ωcm, we have a skin depth of $\delta = 43.3/\sqrt{f}$ and $d/\delta = 0.32\sqrt{f}/43.3 = 7.4 \times 10^{-3}\sqrt{f}$. For a given value of d/δ the corresponding frequency is $f = 135^2 \left(\frac{d}{\delta}\right)^2$.

For cylinder approximations of the vacuum chamber shapes, we have for horizontal ac fields p = 2.09/0.64 = 3.3. From Fig. 2, we see that for p = 3.3, there is no appreciable attenuation up to $d/\delta = 0.3$. This corresponds to a frequency of

$$f = 135^2 \times 0.3^2 = 1640 \text{ Hz}.$$

For vertical fields with p = 7.7/0.64 = 12, we find from Fig. 2 a value $d/\delta = 0.15$ for negligible attenuation, corresponding to a frequency of $f = 135^2 \times 0.15^2 = 410$ Hz. A stainless steel chamber allows corrections up to ~ 400 Hz.

References:

1. W. F. Praeg, "Resistivity, Hysteresis, and Magnetization of 9% Cr Stainless Steel as a Function of Temperature and Its Electromagnetic Shielding Effects in Cylindrical Structures," Proceedings of the 8th Symposium on Engineering Problems of Fusion Research, IEEE Pub. No. 79CH1441-5 NPS, Volume IV.

WP:er

xc:	E. Crosbie	M. Knott	R. Lari	J. Moenich	L. Teng	R. Wehrle
	T. Khoe	R. Kustom	D. McGhee	T. Rauchas	K. Thompson	

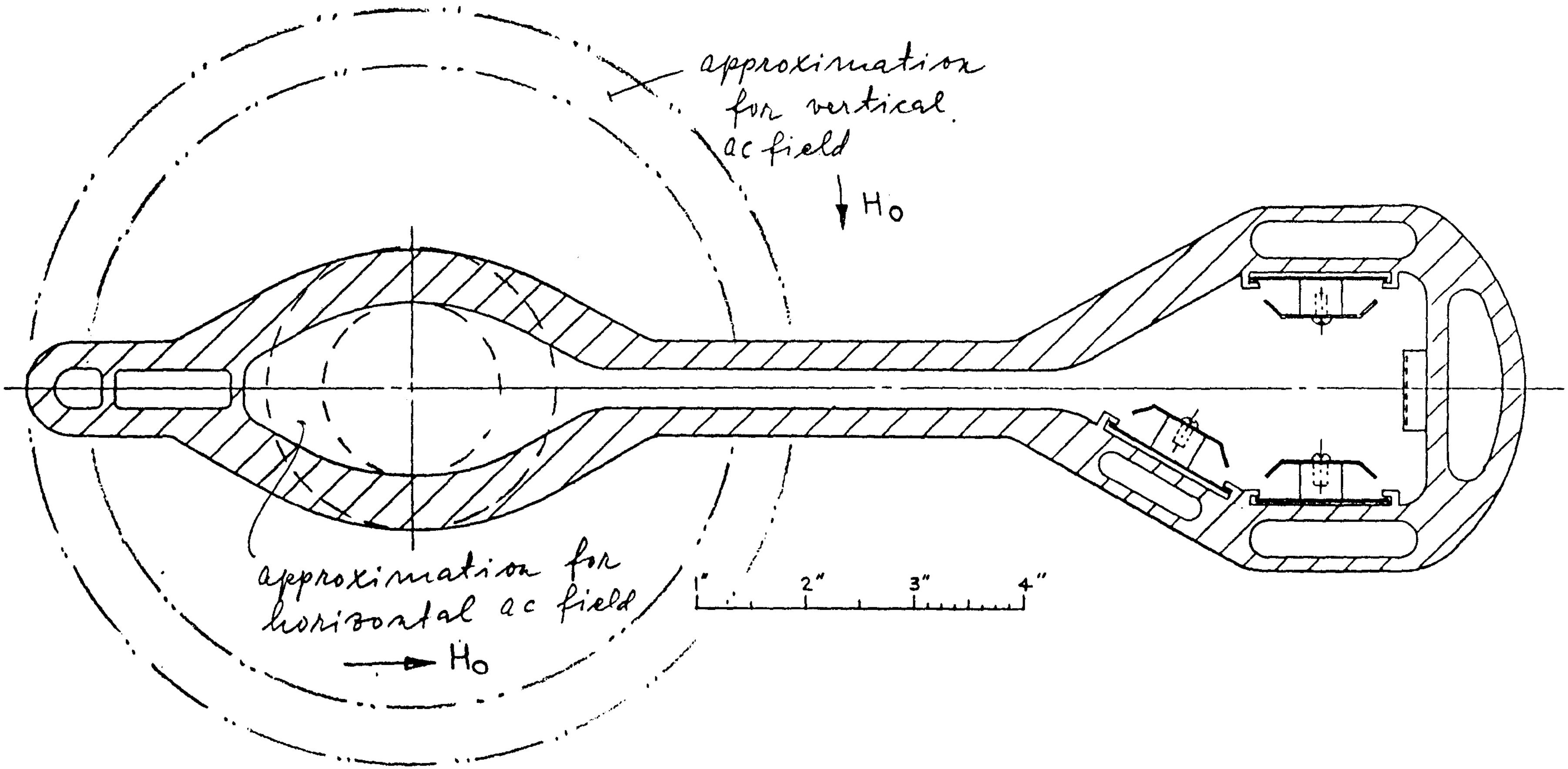


FIG. 1 ALUMINUM VACUUM CHAMBER

REF. NO.

TITLE

FILMED DATE

UNLESS OTHERWISE NOTED
ALL DIMENSIONS ARE INCHES
FRACTIONAL TOL. ± 1/64
DECIMAL TOL. ± .005
ANGULAR TOL. ± 1/4°
REMOVE ALL BURRS AND SHARP EDGES.

DRAWN BY	DATE	GP. LEADER	DATE
CHECKED		PROJECT MGR.	
RESP. ENGINEER		APPR'D/RELEASED	

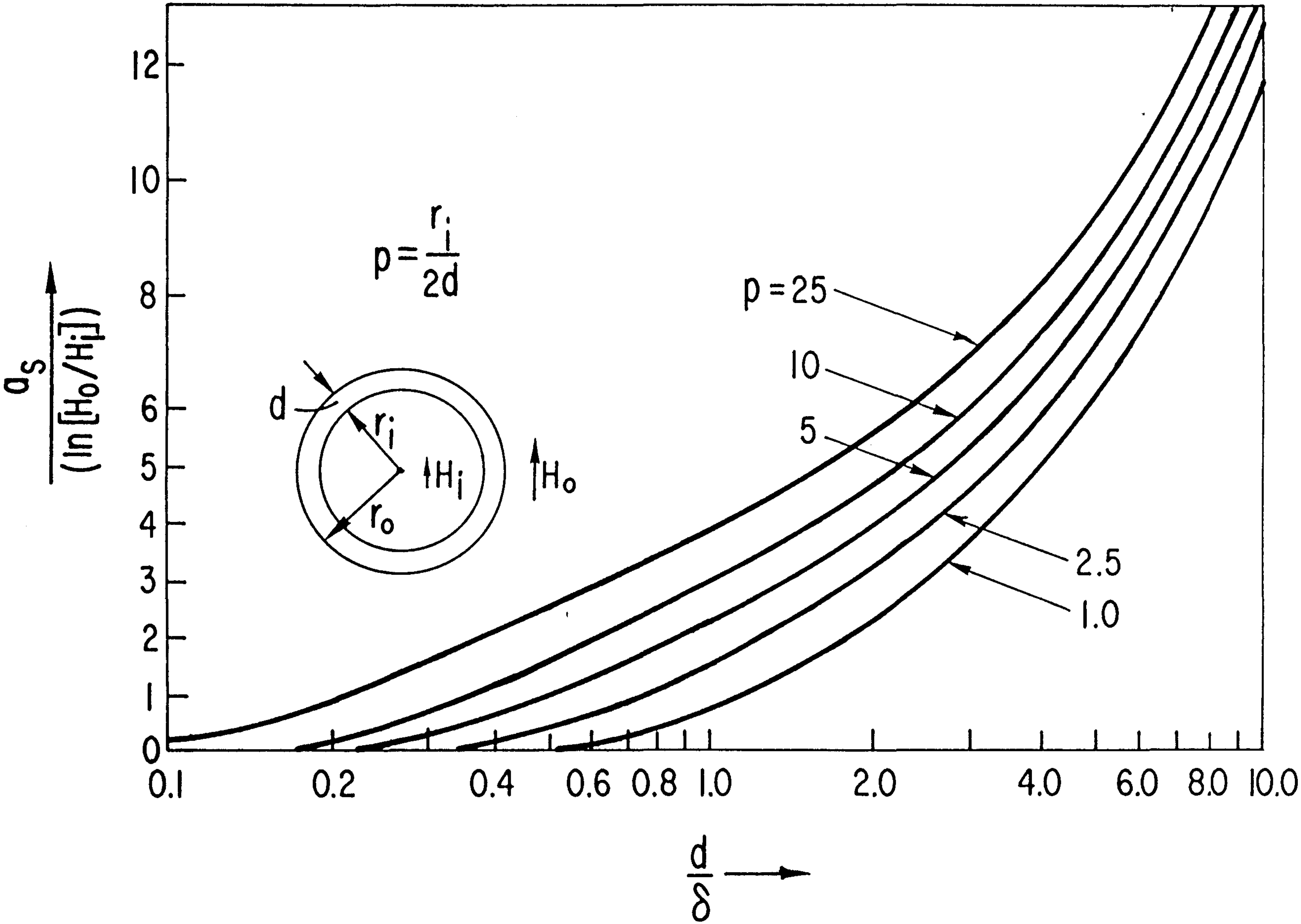


FIG. 2 EDDYCURRENT SHIELDING BY A CYLINDER 12/18/85

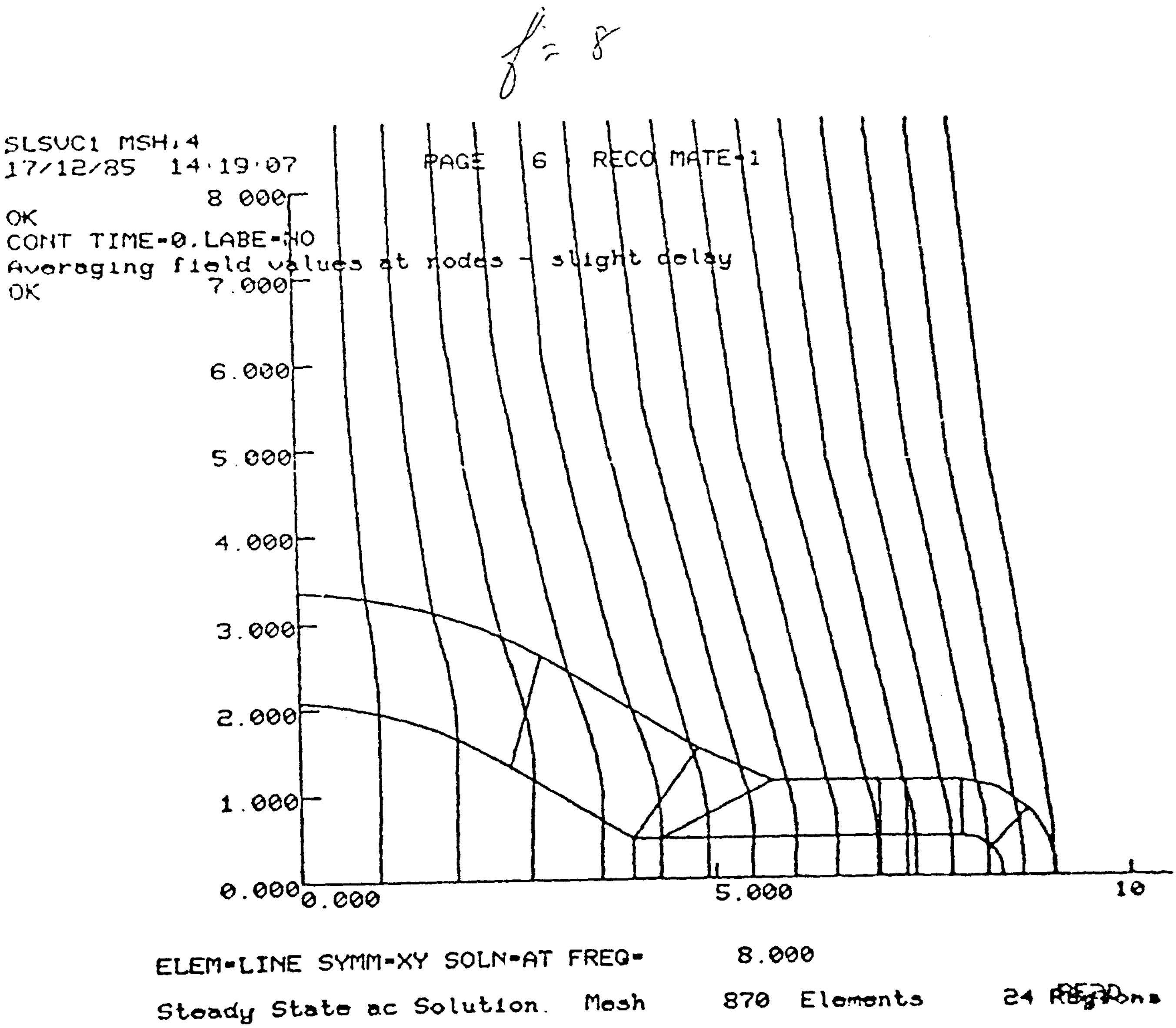


FIG. 3 EDDYCURRENT SHIELDING AT 8Hz

$f = 14$

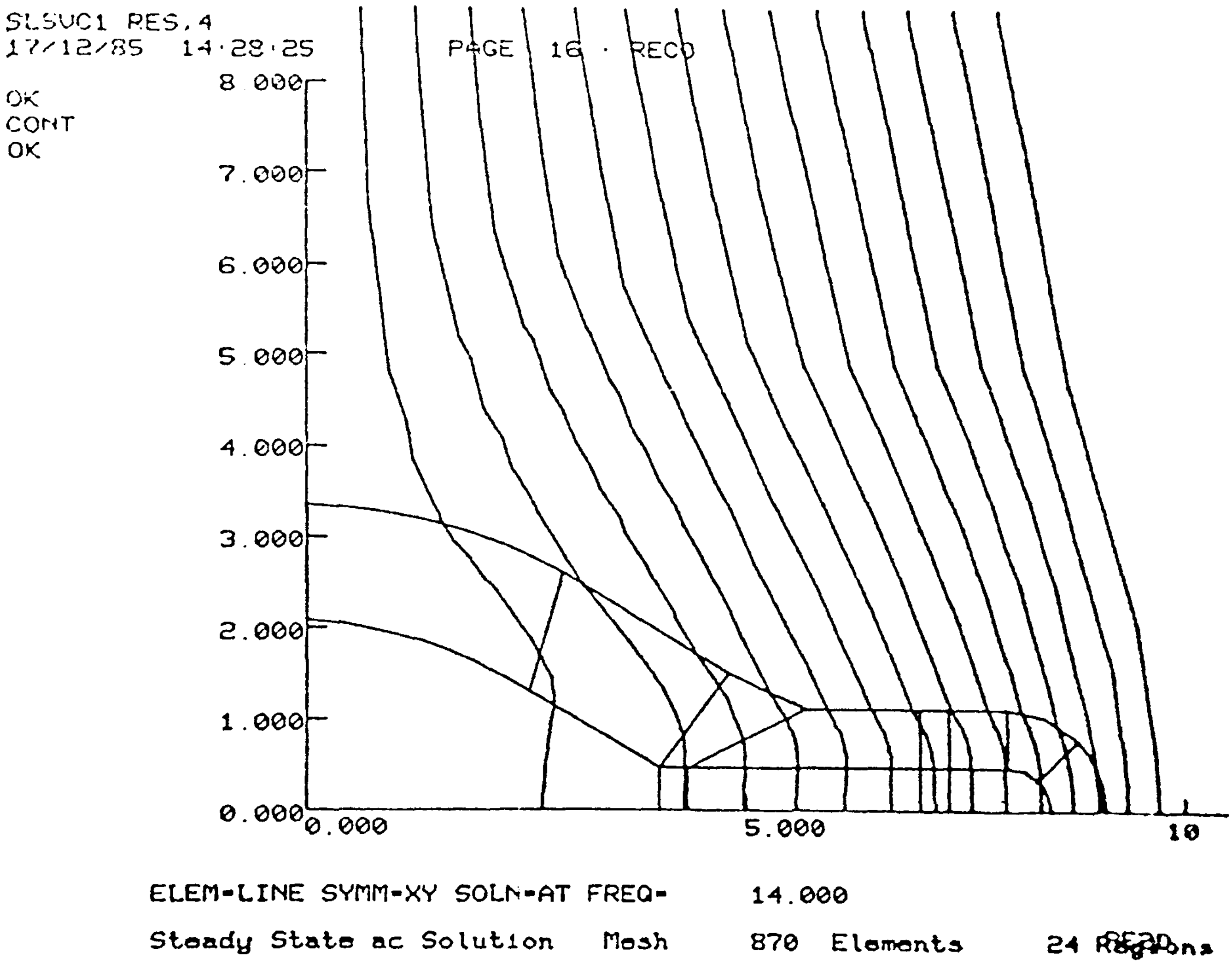
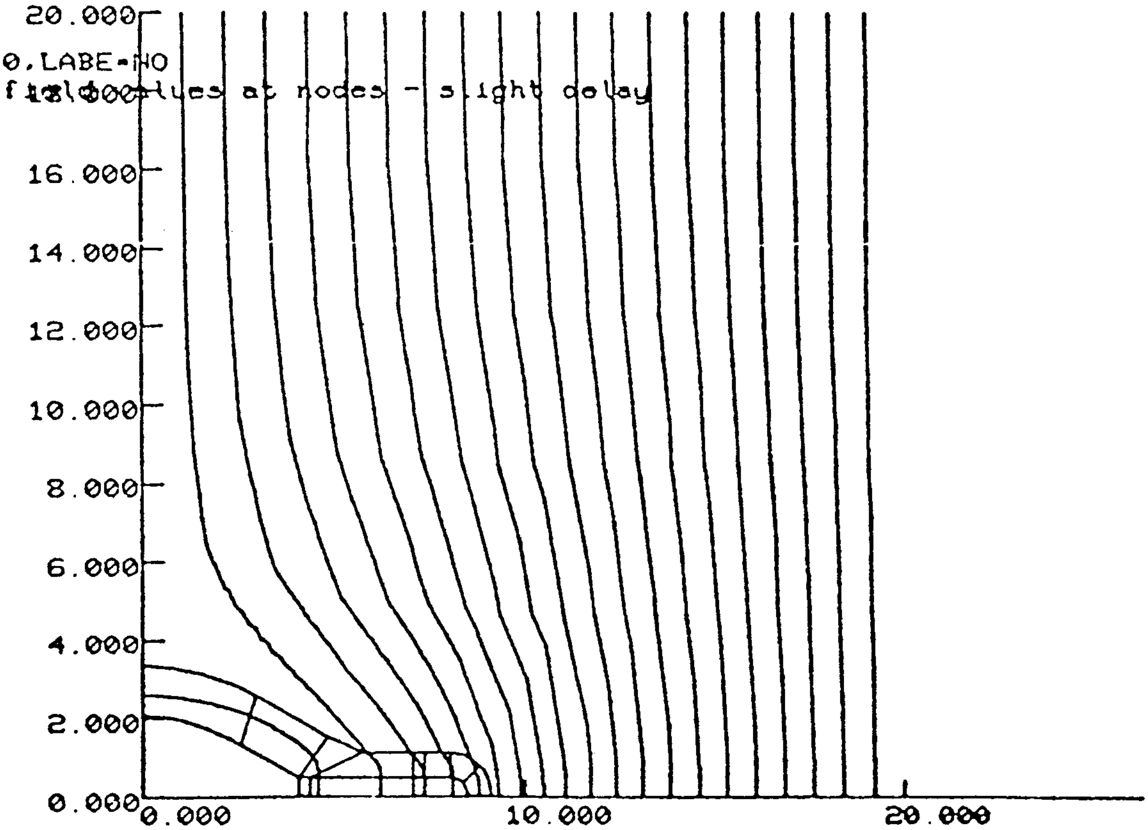


FIG 4 EDDYCURRENT SHIELDING AT 14 Hz.

$f = 25$

SLSVC1.MSH,2
17/12/85 08:55:34 PAGE 11 : RECO

OK
CONT TIME=0,LABE=NO
Averaging field values at nodes - slight delay
OK



ELEM=LINE SYMM=XY SOLN=AT FREQ= 25.000

Steady State ac Solution Mesh 870 Elements 24 Regions PE2D

FIG. 5 EDDYCURRENT SHIELDING AT 25HZ